

iv. Chlorophyll *a* (CHL-*a*)

Chlorophyll is the primary photosynthetic pigment in plants, both algae and macrophytes (*i.e.*, any aquatic plants larger than microscopic algae, including rooted aquatic plants). Because of its prevalence, measurement of chlorophyll can be used to estimate how much algae is present in collected water samples. Chlorophyll *a* (CHL-*a*) is a specific pigment in the chlorophyll family and plays a primary role in photosynthesis (USEPA, 2000).

During the 2001 PALS Snapshot sampling, 191 ponds had surface CHL-*a* samples. The average of concentration of these samples is 8.44 µg/l with a range from 0.01 to 102.9 µg/l. Ahrens and Siver (2000) survey of sixty Cape Cod lakes and ponds found the mean CHL-*a* concentration to be 3.07 µg/l with a range of 0.51 to 19.25 µg/l. Review of the PALS 2001 sampling results established that unimpacted ponds have an average CHL-*a* concentration of 1.0 µg/l (Eichner, *et al.*, 2003).

Hamblin and Middle Ponds have similar CHL-*a* profiles (see Figure 14). Both have average surface concentrations in the 1.7-1.9 µg/l range with higher concentrations deeper in the ponds; Hamblin's 16 m station has an average CHL-*a* concentration of 8.5 µg/l, while Middle's 8.5 m station has an average of 5.4 µg/l (see Table 6). While Hamblin concentrations do not have significant trends over the course of the sampling season, Middle Pond shallow water concentrations significantly increase ($R^2 = 0.87$ at the 0.5 m station and $R^2 = 0.89$ at the 3 m station).

Mystic Lake has a much higher average shallow CHL-*a* concentration than the other two ponds (5 µg/l at 0.5 m station and 5.2 µg/l at the 3 m station)(see Figure 13). These concentrations are similar to the concentration observed at the deepest sampling station in Middle Pond. The 9 m sampling station in Mystic Lake has an average concentration of 9.9 µg/l, while the deepest station (12-13.2 m) has an average concentration of 1.6 µg/l.

5. Overall Assessment: Ecosystem Status and Phosphorus Budget

A. Ecosystem Status Factors

Assessing the ecosystem status of a lake or pond usually starts from trying to develop an understanding what the system would be like if it did not have the impacts of watershed and surrounding land uses. This understanding usually has to be developed by looking at similar, unimpacted ponds and historic water quality measurements. On Cape Cod, developing this understanding is hindered a bit more than in other portions of the country since the Cape's geology and climatic environment are relatively unique.

Carlson (1977) developed a trophic status index based on water quality monitoring available at the time, mostly for ponds in Wisconsin and Minnesota. The trophic state of a pond is the total amount of living biological material (*i.e.*, biomass) in the ecosystem and Carlson's index uses various measures to provide a single index number that places ponds in various trophic categories (Table 7). Carlson designed the system to utilize one or another of the measures to classify the trophic state index (TSI) of a pond or lake on a scale of 0 to 100 (Carlson and Simpson, 1996). Although the Carlson indices were developed for use in northern temperate lakes and do not work well in lakes where macrophytes (*i.e.*, rooted aquatic plants)

dominate the ecosystem, use of this index provides a common touchstone for comparing the Indian Ponds.

During the course of preparing the Cape Cod Pond and Lake Atlas (Eichner, *et al.*, 2003), 2001 PALS Snapshot data was reviewed using a USEPA method for developing nutrient limits (USEPA, 2000). The USEPA method has two approaches for setting a nutrient limit: 1) review all the available data and determine the 25th percentile and 2) look at the data from systems that are “unimpacted” and determine the 75th percentile. When these approaches were applied to the 2001 PALS Snapshot data, the surface water total phosphorus concentrations were 10 and 7.5 µg/l, respectively, while the total nitrogen concentrations were 0.31 and 0.16 ppm, respectively. Chlorophyll *a* concentrations were 1.7 and 1.0 µg/l, respectively. USEPA’s determination of these same factors using the 25th percentile approach for all ponds in the ecoregion that includes Cape Cod, which extends from Maine to Georgia, had the following limits: chlorophyll *a*, 2.1 µg/l; TN, 0.32 ppm; and TP, 8 µg/l.

Table 7. – Carlson Trophic State Index (TSI)					
TSI Calculations					
$TSI(SD) = 60 - 14.41 \ln(SD)$			SD = Secchi disk depth (meters)		
$TSI(CHL) = 9.81 \ln(CHL) + 30.6$			CHL = Chlorophyll <i>a</i> concentration ($\mu\text{g/l}$)		
$TSI(TP) = 14.42 \ln(TP) + 4.15$			TP = Total phosphorus concentration ($\mu\text{g/l}$)		
TSI values and likely pond attributes					
TSI Values	Chl <i>a</i> ($\mu\text{g/l}$)	SD (m)	TP ($\mu\text{g/l}$)	Attributes	Fisheries & Recreation
<30	<0.95	>8	<6	Oligotrophy: Clear water, oxygen throughout the year in the hypolimnion	Salmonid fisheries dominate
30-40	0.95-2.6	8-4	6-12	Hypolimnia of shallower lakes may become anoxic	Salmonid fisheries in deep lakes only
40-50	2.6-7.3	4-2	12-24	Mesotrophy: Water moderately clear; increasing probability of hypolimnetic anoxia during summer	Hypolimnetic anoxia results in loss of salmonids.
50-60	7.3-20	2-1	24-48	Eutrophy: Anoxic hypolimnia, macrophyte problems possible	Warm-water fisheries only. Bass may dominate.
60-70	20-56	0.5-1	48-96	Blue-green algae dominate, algal scums and macrophyte problems	Nuisance macrophytes, algal scums, and low transparency may discourage swimming and boating.
70-80	56-155	0.25-0.5	96-192	Hypereutrophy: (light limited productivity). Dense algae and macrophytes	
>80	>155	<0.25	192-384	Algal scums, few macrophytes	Rough fish dominate; summer fish kills possible

after Carlson and Simpson (1996);
Note: Carlson TSI developed in algal dominated, northern temperate lakes

B. Phosphorus Budget Development

Biomass in pond and lake ecosystems is usually limited by a key nutrient; if more of the nutrient is available the biomass will increase. In ponds and lakes, the key nutrient is usually phosphorus; rapid introduction of phosphorus usually leads to algal blooms, while more gradual increases can prompt the change in the dominant plant community from one dominated by algae to one dominated by rooted plants. Overall, addition of phosphorus increases the biomass in a lake and excessive phosphorus leads to excessive plant growth the decay of which overwhelms natural regeneration processes and leads to anoxic sediment conditions (Wetzel, 1983). One way

to assess whether a lake is limited by phosphorus is to review the balance between phosphorus and nitrogen; as a rule of thumb, if the ratio between nitrogen and phosphorus is greater than 16, phosphorus is the limiting nutrient (Redfield, *et al.*, 1963). Because phosphorus is usually the key nutrient, lake scientists usually develop a phosphorus budget to quantify the primary sources and, if there are water quality problems, to develop targeted strategies to reduce the loads from these sources.

As groundwater flows into Cape Cod ponds along the upgradient shoreline, it brings with it contaminants from the pond watershed, including phosphorus. Phosphorus is chemically more stable in well-oxygenated waters if it is bound with iron (Stumm and Morgan, 1981). Because of this, phosphorus associated with small sources, like septic systems, moves very slowly (~1 m/yr) in groundwater systems, like the Cape, where iron coats sand particles that make up most of our aquifer (*e.g.*, Robertson, *et al.*, 1998). By contrast, a general groundwater flow for Cape Cod is 1 ft/d (or 111 m/yr). Because of this slow movement for phosphorus, most of the sources of phosphorus entering Cape Cod ponds is from properties abutting the pond shoreline; previous analysis of Cape Cod ponds have focused on properties within 300 ft of the shoreline (*e.g.*, Eichner, *et al.*, 1999).

For the Indian Ponds complex, project staff began the development of the watershed portion of the phosphorus budget by looking at properties within 300 ft of the pond shoreline. The list of these properties was then adjusted to assign properties to a given lake only if they were on the upgradient side (Figure 16). Aerial photographs of the properties were reviewed and loads were only assigned to developed properties with houses or other structures within the 300 ft boundary. Properties included in the loading calculations were adjusted, as described below, based on best professional judgment of likely groundwater flow characteristics near the ponds and better balance between observed phosphorus concentrations and those estimated based on the calculated loads. Phosphorus loads were developed based on the factors in Table 8.

Factor	Value	Units	Source
Wastewater P load	1	lb P/septic system	MEDEP, 1989
Road surface P load	5.3	lb P/ac	MEDEP, 1989
Natural Areas P conc.	0.014	mg P/l	BEC, 1993
Recharge Rate	27.25	in/yr	Walter and Whealan, 2005
Building Area	Actual value	ft ²	Town of Barnstable Assessor Information
Road Area	Actual value	ft ²	Mass. Highway Information
Lawn Factors			
Area per residence	5,000	ft ²	Eichner and Cambareri, 1992
Fertilizer lawn load	0.3	lb P/ac	MEDEP, 1989
Waterfowl Factors			
P load	0.156	g/m ² /yr	Scherer, <i>et al.</i> , 1995
New P load	13	%	Scherer, <i>et al.</i> , 1995

i. Mystic Lake

Mystic Lake is an impacted pond with water quality problems. The lake thermally stratifies during the summer and the deeper waters are cut off from direct interaction with the atmosphere (see Figure 10). Oxygen in these deep waters is consumed by sediment oxygen demand relatively soon after stratification; these anoxic conditions were measured at the earliest readings collected during this study (May 19, 2004). The anoxic conditions indicate that more organic material is present in and falling to the sediments than can be digested (or broken down) by its bacterial population. Average hypolimnetic sediment oxygen demand is estimated at 358 mg/m²/d. These anoxic conditions create chemical conditions that cause nutrients that would otherwise be bound in the sediments to be released back into the overlying water column. Deep TN and TP concentrations increase relatively linearly throughout the summer (0.02 ppm TN per day and 7 ppb TP per day).

These increases are also seen at the 9 m interface between the upper, well-mixed epilimnion and the deep hypolimnion. The average TP concentration at 9 m is twice the concentrations seen at the 0.5 and 3 m sampling depths and the 9 m chlorophyll *a* average is nearly twice seen in the upper waters (see Figure 14). These 9 m concentrations suggest that nutrients from the hypolimnion are mixing into the epilimnion, but the relatively stable concentrations in the epilimnion suggest that the mass mixing is relatively constant. TP mass in the upper waters (0.5 and 3 m) fluctuates in a relatively constrained range between 31 and 62 kg and individual sampling date results show no trend throughout the summer.

The surface TP and chlorophyll *a* concentrations are high compared to other Cape Cod ponds and show that the system is clearly impacted. The average TP concentration of the upper two sampling depths is 16 ppb, which is higher than the 10 ppb developed as an impacted threshold for Cape Cod ponds (Eichner, *et al.*, 2003). This TP concentration and the 5.1 ppb average chlorophyll *a* concentration place this lake in the mesotrophic category in the Carlson and Simpson (1996) trophic index. Lakes in this category are characterized as: “water moderately clear; increasing probability of hypolimnetic anoxia during summer” and fisheries are characterized as “hypolimnetic anoxia results in loss of salmonids.” Secchi readings are consistent with other readings, showing that the average reading in the lake is 3 m or 22% of the total depth, both of which are the lowest among the three Indian Ponds (see Figure 12).

Nutrient concentrations are consistent with phosphorus limitation in Mystic Lake. TN to TP concentration ratios in the epilimnion average 42, which is more than twice the Redfield limit of 16, and solidly supports phosphorus limitation in Mystic Lake. Ratios of samples from deeper in the lake are also two to six times the Redfield limit.

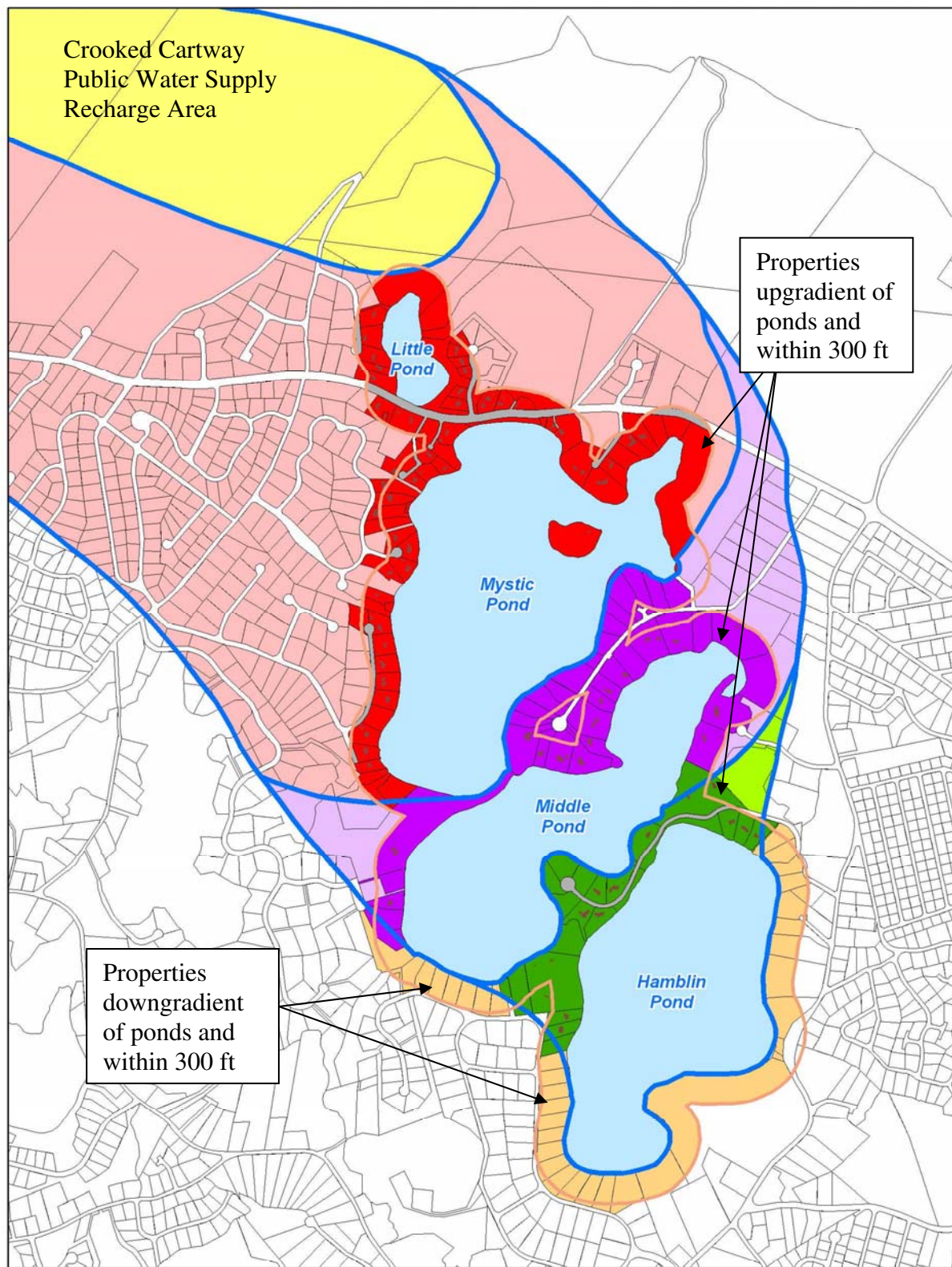


Figure 16. Properties considered in watershed phosphorus loading analysis for Indian Ponds

Although the 1948 MADFG data is the only significantly older data available, comparison of these dissolved oxygen and temperature profiles to data collected in August during this study and PALS snapshot profiles from the past four years seem to indicate that conditions in the Mystic Lake have become more impaired over the last 50 years (see Figure 13). The August 1948 temperature profile is similar to the ones collected during the PALS snapshot. However, the 1948 dissolved oxygen profile has anoxic conditions at a depth of 12 m, while the more recent data has anoxic conditions at 9 m. The recent readings are notable because this depth is the bottom of the epilimnion. This comparison means that sediment regeneration of nutrients in 1948 would not have reached the epilimnion because there would be a layer of well-oxygenated water between 9 and 12 m that would have essentially prevented the leaking of TP to the epilimnion that is seen in the 2004 data. This “bleed through” has been observed in other Cape Cod ponds that are similarly impaired (e.g., ENSR, 2001).

The release of TP from the sediments is the primary source of phosphorus in Mystic Lake (Figure 17). This portion of the phosphorus budget is based on lake-specific water quality measurements; phosphorus in the hypolimnion increases throughout the summer, the TP load increasing from 30 kg in May to 330 kg in mid-September. Because of this, the sediment portion of the phosphorus budget increases from 34% to 88% and the total mass of TP increases from 88 to 375 kg. The average hypolimnetic mass was used to develop the internal regeneration portion of the phosphorus budget shown in Figure 17.

The rest of the phosphorus budget for Mystic Lake is the load that comes from its watershed and, mostly, the properties that abut the lake. The two primary constituents of the watershed phosphorus budget are wastewater and waterfowl (see Figure 17). The wastewater load (41% of the watershed budget) is based on septic systems on the properties within 300 ft (see Figure 16). The waterfowl load is based on a factor developed in a highly detailed study of bird feeding and phosphorus loading (Scherer, *et al.*, 1995); similar site-specific data is not available. Long time IPA members remember significant gull populations gathering on Middle Pond, in particular; these flocks have largely disappeared following the capping of the town landfill. Further review of the factors used in the phosphorus load suggests that the simple budget could be refined, but this would require the collection of additional site-specific data.

Studies of septic system effluent have shown that the phosphorus portion of a system groundwater plume moves at approximately 1 m per year (e.g., Robertson, *et al.*, 1998). This flow rate means that phosphorus would need 91 years to traverse 300 ft. Based on a review of town Board of Health and Building Department records by Holly Hobart of the IPA, the average age of residences within the 300 ft buffer is 35 years old (*i.e.*, built in 1970). The average distance for the septic system leachfields for these properties is 196 ft. Using the 1 m/y phosphorus travel time, the average time for phosphorus from the average property abutting Mystic Lake to reach the lake is ~60 years. Given that the average travel time is greater than the average age of the residences, this analysis suggests that the wastewater, fertilizer, and road portions of the phosphorus budget should be reduced by 42%. Further, this analysis also suggests that the observed nutrient concentrations in the pond are likely to increase as phosphorus already in the groundwater reaches the lake. The in-lake phosphorus budget shown in Figure 17 reflects an adjustment in these portions, so the budget is based on existing

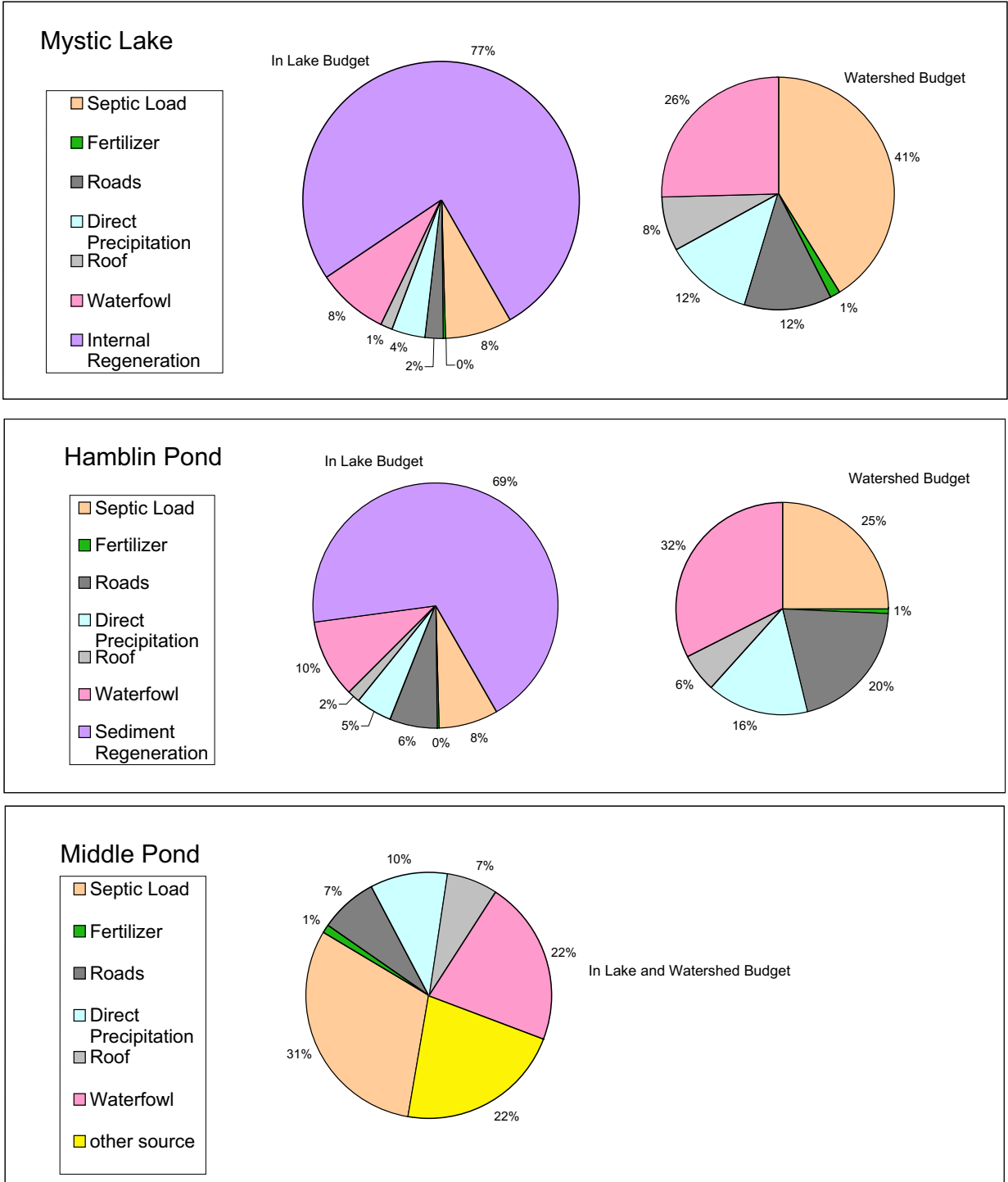


Figure 17. Phosphorus Budgets for the Indian Ponds.
 Sediment regeneration is based on median phosphorus mass calculated from 2004 water quality data; watershed loads are estimated based on factors in Table 8 with adjustments to account for phosphorus time of travel.

conditions. The watershed budget is based on steady state conditions and does not include modification to account for phosphorus time of travel.

Project staff checked the balance between the modeled watershed recharge coming into the pond, the calculated phosphorus load, and the observed concentrations in the pond; this analysis suggested that observed concentrations in the pond were better matched if the recharge was reduced by removing the recharge within the watersheds to the public water supply wells. This analysis suggests that most of the water pumped by these wells is not discharged within the Indian Ponds watershed.

The average calculated TP mass in the epilimnion of Mystic Lake is 45.7 kg. The adjusted watershed load, incorporating modifications to account for delays in phosphorus travel time, accounts for 35.2 kg. In order to bring the lake TP budget into balance, 12.3 kg of TP would have to be added. Based on the observed TP data, the most likely source of this load is from the hypolimnion. Average TP and chlorophyll *a* concentrations at 9 m are close to double the concentrations above them; given that 9 m is generally in the metalimnion (*i.e.*, the transition zone between the upper and lower layers), these concentrations are consistent with a conclusion that nutrients are generally leaking up from the hypolimnion. This hypothesis is also consistent with the estimated sediment oxygen demand. Five additional houses are projected within the 300 ft buffer area at buildout; this will increase the annual steady state watershed TP load at buildout to 50.2 kg.

ii. Middle Pond

Middle Pond is a well-mixed pond with generally good water quality characteristics, but with concerns. The pond does not thermally stratify since its maximum depth is only slightly deeper than the stratification depth of most ponds on Cape Cod (~9m) and because of this normal wind energy is sufficient to keep the water column generally well mixed throughout the summer (see Figure 10). This mixing allows oxygen to be mixed into the water column on a regular basis, but even with this availability the pond occasionally develops anoxic conditions near the sediments. Average sediment oxygen demand is estimated at 109 mg/m²/d.

Concentrations of TP and TN are relatively stable during the summer, but chlorophyll *a* concentrations have a significant upward trend. Sampling at the shallowest station had an average TP concentration of 15 ppb, while lower concentrations deeper in the pond produce an overall average concentration of 10.6 ppb (see Figure 14). This overall concentration is approximately the same as the 10 ppb impacted threshold developed from a review of over 180 Cape Cod ponds (Eichner, *et al.*, 2003). Average TN concentrations are similar at all depths (0.26 to 0.28 ppm) with an overall pond average of 0.27 ppm. Comparison of TN and TP concentrations on individual sampling dates and averages at all three sampling depths indicate that the pond is phosphorus limited; the average lake-wide ratio is 82.

Middle Pond's average surface TP and chlorophyll *a* concentrations place this lake in the high oligotrophic mesotrophic category in the Carlson and Simpson (1996) trophic index. Lakes in this category are characterized as: "hypolimnia of shallower lakes, may become anoxic" and fisheries are characterized as "salmonid fisheries in deep lakes only." These characterizations illustrate some of the issues with applicability of this index, in general, to shallower lakes that do not stratify and, specifically, to Cape Cod ponds and lakes.

Although the 1948 MADFG data is the only significantly older data available, comparison of these dissolved oxygen and temperature profiles to data collected in August during this study and PALS snapshot profiles from the past four years seem to indicate that conditions in the Middle Pond have become more impaired over the last 50 years (see Figure 13). The deepest dissolved oxygen reading (9 m) in the August 1948 profile has full saturated conditions, while all the more recent data has anoxic conditions at 9 m. This comparison suggests that the pond is receiving more nutrients than it did in the past and that the current load has exceeded the capacity of the sediments to process this load during oxygenated conditions.

Shallow (0.5 and 3 m) chlorophyll *a* concentrations average 1.9 µg/l, which is higher than the Cape Cod 1 µg/l impacted threshold (Eichner, *et al.*, 2003). In addition, these readings have a significant upward trend ($R^2=0.89$) as the summer progresses. This is inconsistent with the TP concentrations, which fluctuate somewhat but within a relatively constrained range. Secchi readings show a similar trend with a slightly weaker relationship ($R^2=0.52$; 13 mm reduction in Secchi depth per day), but this trend suggests that the chlorophyll readings are accurate. Further analysis of food chain dynamics (*e.g.*, variations in composition of phyto- and zooplankton populations) and chemical interactions would be necessary to resolve why there is an apparent disconnect between TP and chlorophyll *a* concentrations. The only likely sources of additional TP that could prompt chlorophyll *a* increases and Secchi depth decreases would be sediment regeneration or phosphorus coming from Mystic Lake.

When the phosphorus budget for Middle Pond is worked up, there is a deficiency after accounting for all the known sources (listed in Table 8). The primary accounted sources are waterfowl (22%) and septic systems (16%). TP from septic systems is from properties mostly abutting the pond, plus all the properties on the land bridge between Middle Pond and Mystic Lake (see Figure 16). The land bridge properties were included because, even though these properties are beyond the 300 ft buffer, groundwater from them would have to discharge to Middle Pond. In order to have the calculated TP sources balance the measured TP based on the water quality data, approximately 14 kg needs to be added; this is labeled “other source” in Figure 17.

This analysis of the budget includes an adjustment to account for delays of phosphorus reaching the pond from watershed sources. Studies of septic system effluent have shown that the phosphorus portion of a system groundwater plume moves at approximately 1 m per year (*e.g.*, Robertson, *et al.*, 1998). This flow rate means that phosphorus would need 91 years to traverse 300 ft. Based on a review of town Board of Health and Building Department records by Holly Hobart of the IPA, the average age of residences included in the watershed load to Middle Pond is 32 years old (*i.e.*, built in 1973). The average distance for the septic system leachfields for these properties is 187 ft. Using the 1 m/y phosphorus travel time, the average time for phosphorus from the average property abutting Middle Pond to reach the pond is ~57 years. Given that the average travel time is greater than the age of the residences, this analysis suggests that the wastewater, fertilizer, and road portions of the watershed phosphorus budget should be reduced by 44%. Further, this analysis also suggests that the observed nutrient concentrations in the pond are likely to increase as phosphorus already in the groundwater reaches the lake. The in-lake phosphorus budget reflects an adjustment in these portions (see Figure 17), so the budget

is based on existing conditions. The watershed budget is based on steady state conditions and does not include modification to account for phosphorus time of travel.

Since Middle Pond's sediments and Mystic Lake were potential additional TP sources, staff reviewed the likelihood of these two sources supplying the TP necessary to balance the budget. The water budget has 3,113,379 m³ annually discharging from Mystic Lake (see Table 4); if this volume is multiplied by the average epilimnetic TP concentration (17 ppb), 53 kg of TP would be available to be discharged to Middle Pond. The load needed to balance the phosphorus budget would be 26% of this mass. The length of the downgradient shoreline at the land bridge between Mystic Lake and Middle Pond is approximately 13% of the total shoreline, so an approximate calculation would estimate that half of what is needed would flow through this portion. The regular water connection between the ponds at the north edge of the land bridge could focus this mass transfer, although additional characterization of this connection would be necessary to quantify its impact. This connection, the low elevation of this land bridge, its width (no more than 10 feet across at the closest point between the ponds), and past observations that it has been submerged during high groundwater conditions suggest that the phosphorus mass crossing it may be greater than half of the load needed to balance the phosphorus budget. At the very least, it is fairly easy to justify Mystic Lake as a partial source to the phosphorus budget of Middle Pond.

Sediment regeneration is more constrained than transfer from Mystic Lake because it would need to occur during the limited period when anoxia occurs over the sediments in Middle Pond. Anoxic conditions are necessary to favor release of TP from the sediments; these conditions occur in late July through mid-September in both the 2004 and 2005 dissolved oxygen profiles. In order to generate ~14 kg worth of TP needed to balance the budget and sustain it in the pond, ~0.6 kg of TP would need to be released daily during the month and a half of deep water anoxia. Given that Mystic Lake's sediments can release TP at a rate of 4.1 kg/d over a similar time period, sediment regeneration is also a possible source of the additional phosphorus necessary to balance Middle Pond's phosphorus budget. However, water quality data do not show higher TP concentrations deep in the ponds (see Figure 14).

As with Mystic Lake, the wastewater and sediment/Mystic Lake portions of the Middle Pond phosphorus budget are more certain than the waterfowl portion (22% of the budget); this estimate is based on a highly detailed study (Scherer, *et al.*, 1995). Long time IPA members remember significant gull populations gathering on Middle Pond; these flocks have largely disappeared following the capping of the town landfill. Additional site-specific study would be necessary to clarify how similar the waterfowl population at Middle Pond is to those used to develop the waterfowl phosphorus-loading factor.

With the addition of ~14 kg of TP, the overall phosphorus budget compares reasonably with the water quality data. The overall annual watershed load to Middle Pond is 39 kg. Two additional houses are projected within the 300 ft buffer area at buildout; this will increase the annual steady state watershed TP load at buildout to 40 kg. The existing load is nearly twice the observed load in the pond (22 kg) based on water quality data; the annual watershed load needs to be nearly twice as much as the load in the pond because the residence time of water in the pond is exchanged every 0.56 years (6.7 months) (see Table 3).

iii. Hamblin Pond

Hamblin Pond is an impacted pond with water quality problems, but much improved over the problems that existed prior to the 1995 alum treatment (BEC, 1993). Currently, the lake thermally stratifies during the summer and the deeper waters are cut off from direct interaction with the atmosphere (see Figure 10). Water quality data shows that oxygen in these deep waters is consumed by sediment oxygen demand relatively soon after stratification; the deepest DO concentrations were less than 2 ppm at the initial profile (May 20, 2004) and were anoxic (<1 ppm) when the next profile was measured (June 9). These conditions indicate that more organic material is present in and falling to the sediments than can be digested (or broken down) by its bacterial population. Average sediment oxygen demand is estimated at 219 mg/m²/d. These anoxic conditions create chemical conditions that cause nutrients that would otherwise be bound in the sediments to be released back into the overlying water column.

Review of nutrient and chlorophyll concentrations at the upper three sampling depths indicates, however, that the release of sediment nutrients does not significantly impact the upper waters of the pond during the summer. Concentrations of TP, TN, and chlorophyll *a* at these stations fluctuate, but do not show significant upward trends. Analysis of the mass of phosphorus in the upper waters also shows fluctuations in the total mass, but no upward trend.

The surface TP and chlorophyll *a* concentrations reflect some of the mix of good and impacted water quality that is seen in Hamblin Pond. The average surface TP concentration is 8.4 ppb, which is less than the 10 ppb impacted threshold developed by the Commission for Cape Cod ponds (Eichner, *et al.*, 2003). The average chlorophyll *a* concentration, on the other hand, is 2.0 µg/l, which is twice the 1.0 µg/l threshold developed by the Commission. Both average concentrations place this lake in the upper oligotrophic category in the Carlson and Simpson (1996) trophic index. Lakes in this category are characterized as: “hypolimnia of shallower lakes, may become anoxic” and fisheries are characterized as “salmonid fisheries in deep lakes only.” Secchi readings are consistent with other readings, showing that the average reading in the lake is 6.4 m or 38% of the total depth; the depth reading is the deepest among the three Indian Ponds, while the relative reading is between the averages for Middle and Mystic (see Figure 12).

Nutrient concentrations are consistent with phosphorus limitation in Hamblin Pond. TN to TP concentration ratios in the epilimnion average 95, which is nearly six times the Redfield limit of 16, and solidly supports phosphorus limitation in Hamblin Pond. Ratios of samples from the deepest portion of the lake show the impact of phosphorus release from the sediments; the average ratio is 38 and some sampling dates the ratio dips slightly below the Redfield limit.

Comparison of dissolved oxygen and temperature profiles collected in 1948 by MADFG and in 1992 by BEC to data collected in August during this study and PALS snapshot profiles from the past four years indicate that conditions in the Hamblin Pond have improved as a result of the 1995 alum application, but that water quality impairments still persist (see Figure 13). The August 1948 and August 1992 dissolved oxygen profiles have anoxic conditions at a depth of 8 and 7 m, respectively. The more recent data have anoxic conditions at 12 m. This means that the alum application recovered ~6 m worth of oxygenated depth and 335 million gallons worth

of oxygenated water. In addition, because oxygenated conditions now extend beyond 9 m (the thermal stratification boundary), there is now an oxygenated buffer that provides some protection from the deeper anoxia and the accompanying high TP concentrations. This is similar to the conditions that existed in Mystic Pond in 1948 (see Figure 13).

The release of TP from the sediments is the primary source (69%) of phosphorus in Hamblin Pond (see Figure 17). This portion of the phosphorus budget is based on the water quality measurements. Although this load fluctuates based on individual sampling dates, phosphorus in the hypolimnion generally has an increasing trend throughout the summer; the hypolimnetic TP load starts at 23 kg in May and climbs as high as 267 kg in early September. The sediment portion of the phosphorus budget fluctuates between 27 and 95% of the total mass of TP in the pond. Staff used the average hypolimnetic mass to develop the internal regeneration portion of the phosphorus budget shown in Figure 17.

The rest of the phosphorus budget for Hamblin Pond is the load that comes from its watershed. The watershed loads (*i.e.*, wastewater, fertilizer, road, roof, direct precipitation, and waterfowl loads) are developed using the factors common to all the ponds (see Table 8); the two primary constituents of the watershed phosphorus budget are wastewater (25%) and waterfowl (32%) (see Figure 17). As with the other two ponds, the wastewater and sediment regeneration portions of the phosphorus budget are more certain than the waterfowl portion; this estimate is based on a highly detailed study (Scherer, *et al.*, 1995), but additional study would be necessary to clarify how similar the waterfowl population at Hamblin Pond is to the study lake. This analysis includes TP from septic systems on properties mostly abutting the pond, plus all the properties on the land bridge between Middle Pond and Hamblin Pond (see Figure 16). The land bridge properties were included because, even though these properties are beyond the 300 ft buffer, groundwater from them would have to discharge to Hamblin Pond. The good match between observed water quality and estimated TP loads suggests that phosphorus from Middle Pond does not traverse the land bridge between Middle Pond and Hamblin Pond. The sum of all these loads is 24 kg and this approximately matches the average load in the epilimnion of 26.9 kg developed based on water quality data. Based on the analysis of properties within the 300 ft buffer, there are no additional residences projected at buildout.

This analysis of the budget includes an adjustment to account for delays of phosphorus reaching the pond from watershed sources. Studies of septic system effluent have shown that the phosphorus portion of a system groundwater plume moves at approximately 1 m per year (e.g., Robertson, *et al.*, 1998). This flow rate means that phosphorus would need 91 years to traverse 300 ft. Based on a review of town Board of Health and Building Department records by Holly Hobart of the IPA, the average age of residences included in the watershed load to Hamblin Pond is 31 years old (*i.e.*, built in 1974). The average distance for the septic system leachfields for these properties is 154 ft. Using the 1 m/y phosphorus travel time, the average time for phosphorus from the average property abutting Hamblin Pond to reach the pond is ~47 years. Given that the average travel time is greater than the age of the residences, this analysis suggests that the wastewater, fertilizer, and road portions of the watershed phosphorus budget should be reduced by 34%. Further, this analysis also suggests that the observed nutrient concentrations in the pond are likely to increase as phosphorus already in the groundwater reaches the lake. The in-lake phosphorus budget reflects an adjustment in these portions (see Figure 17), so the budget

is based on existing conditions. The watershed budget is based on steady state conditions and does not include modification to account for phosphorus time of travel.

In summary, the apportionment of the watershed load into the various categories could require some additional work to refine and confirm, but the overall budget compares reasonably with the water quality data. This comparison also supports the assessment that deeper, hypolimnetic sediment regeneration of TP is not significantly impacting the upper, epilimnetic waters of Hamblin Pond.

6. Conclusions

After reviewing the water quality data, it is clear that Mystic Lake is impaired. Water quality in the other two ponds shows some issues of concern, but water quality conditions are generally good.

Mystic Lake's impairments are the result of total phosphorous entering the lake from its watershed and being regenerated from its sediments. Anoxic conditions in the hypolimnion that have occurred over the last 50 years allow TP to be released from the sediments back into the water; TP in the sediments originally came from the watershed, was utilized by phytoplankton in the lake, and fell to the sediments when the phytoplankton died. So much TP is being released from the sediments that it is leaking through the bottom of the epilimnion and prompting higher TP and chlorophyll *a* concentrations in this upper layer, as well as lower Secchi readings. Current phosphorus loading from the lake's watershed is approximately 35 kg/yr, while sediment regeneration is estimated as 12 kg/yr. Watershed loads are projected to increase to 47 kg/yr at steady state without any additional development along the shoreline and 50 kg/yr at full buildout. TP management activities should address the sediment regeneration and the existing and future watershed sources.

Middle Pond has surface water phosphorus concentrations that are just above the impacted threshold of 10 ppb determined by the Cape Cod Commission (Eichner, *et al.*, 2003). Chlorophyll *a* concentrations and Secchi depth readings have significant summer-long trends indicating worsening conditions in the pond. Current watershed phosphorus loading is approximately 23 kg/yr plus an additional ~14 kg/yr from sediment regeneration and/or direct input from Mystic Lake. Watershed loads are projected to increase to 40 kg/yr at steady state without any additional development along the shoreline and two additional lots at buildout will increase this load less than one additional kilogram per year.

Hamblin Pond has surface water phosphorus concentrations that are just below the 10 ppb threshold, but anoxic conditions that allow sediment regeneration of phosphorus exist deeper in the pond. Fortunately, the 1995 alum treatment reduced sediment oxygen demand sufficiently to reestablish a fully oxygenated layer within the hypolimnion. The above analysis indicates that this oxygenated layer is preventing regenerated phosphorus from prompting phytoplankton growth in the epilimnion. Current watershed phosphorus loading is approximately 24 kg/yr. Watershed loads are projected to increase to 29 kg/yr at steady state without any additional development along the shoreline and there are no projected additions at buildout.